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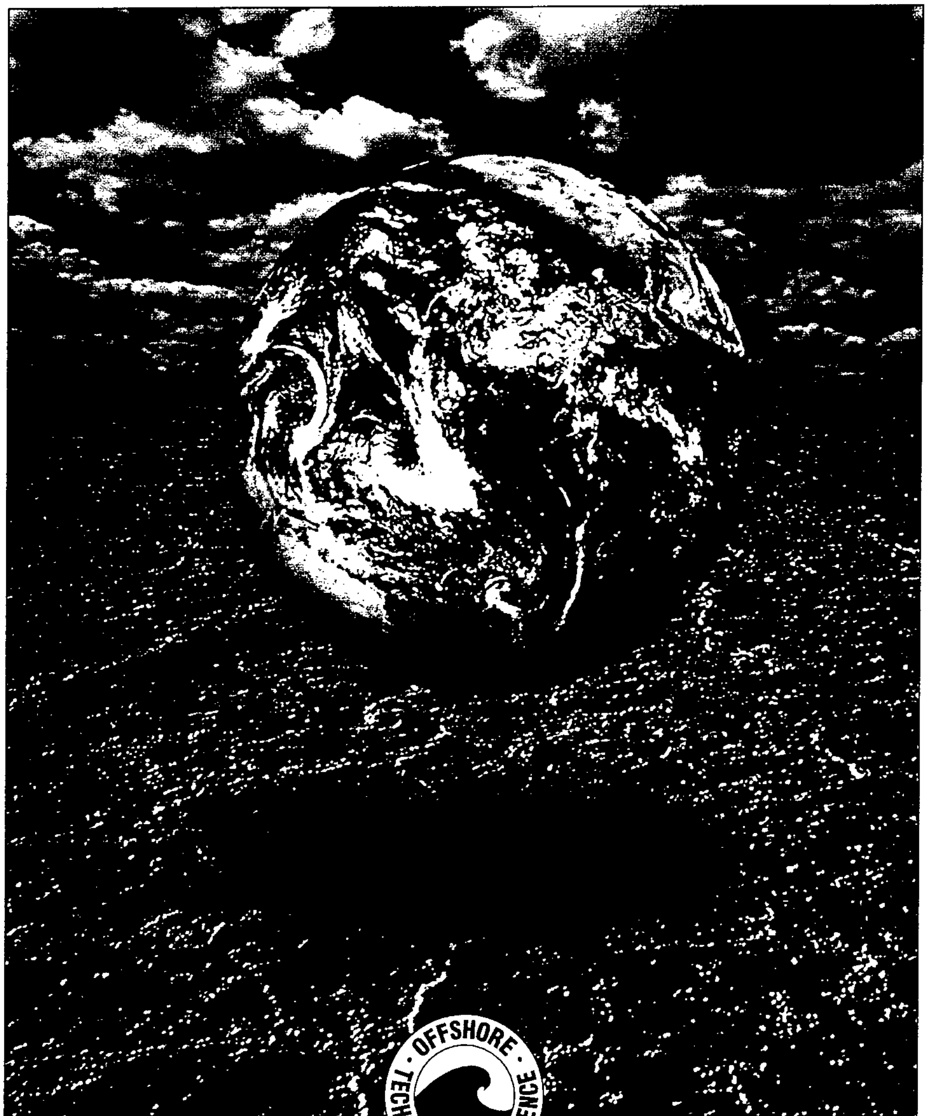

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Offset-vertical seismic profiling for marine gas hydrate exploration - is it a suitable technique? First results from ODP Leg 164

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Abstract
Walkaway vertical seismic profiles were acquired during Ocean Drilling Project (ODP) Leg 164 at the Blake Ridge to investigate seismic properties of hydrate-bearing sediments and the zone of free gas beneath them. An evaluation of compressional (P-) wave arrivals Site 994 indicates P-wave anisotropy in the sediment column. We identified several shear (S-) wave arrivals in the horizontal components of the geophone array in the borehole and in data recorded with an ocean bottom seismometer deployed at the seafloor. S-waves were converted from P-waves at several depth levels in the sediment column. One of the most prominent conversion points appears to be the bottom simulating reflector (BSR). It is likely that other conversion points are located in the zone of low P-wave reflectivity above the BSR. Modeling suggests that a change of the shear modulus is sufficient to cause significant shear conversion without a significant normal-incidence P-wave reflection.

Introduction
Seismic methods appear to be the most promising approach for indirect detection and quantification of gas hydrates. However, our knowledge of the effect of methane gas hydrate on the seismic properties of natural sediments is still very limited. One of the major goals of ODP Leg 164 at the Blake Ridge offshore South Carolina was to investigate physical properties of hydrate-bearing sediment. The Blake Ridge offered an ideal "natural laboratory" for these types of studies. It is a geologically stable region, unlike areas of gas hydrate occurrence on convergent margins, and hence, hydrate-related changes of sediment properties can be more easily delineated from changes due to the geological setting.

Theoretical studies of compressional (P-) and shear (S-) wave velocity demonstrate that hydrates could affect these properties, due to the high seismic velocities of pure methane hydrate compared to natural sediments. The P-wave velocity (V_p) of methane hydrate has been measured as 3.3-3.8 km/s [1]. The S-wave velocity (V_s) is assumed to be about 1.7 km/s, based on a laboratory study of propane hydrate[2] and the similarity of hydrate to water ice[3]. The effect of hydrate on seismic properties of natural sediments largely depends, however, on the distribution of hydrate in the sediment[4]. Hydrate disseminated within the pore space is believed to only moderately increase V_p and to have almost no effect on V_s, since V_s is controlled mainly by sediment matrix properties[5]. If hydrate acts as a cementing agent between grains, the effect on V_p is assumed to be larger, and V_s may increase significantly due to stiffening of the matrix. Hydrates being distributed macroscopically, i.e. as bodies considerably larger than the pore size, would yield a time-averaged[6] velocity of methane hydrate and the rest of the sediment column.

Vertical seismic profiles (VSPs) were collected on the Blake Ridge to determine seismic velocities in the hydrate-bearing sediments and relate them to hydrate concentration. The analysis of zero-offset VSPs, in which the seismic source was located close to the drillship and receivers were moved vertically at 8 m spacing within the borehole, yielded an accurate V_p-model for waves traveling through the sediment column at normal incidence[7]. Walkaway (or variable-offset) VSP profiles were acquired, for which the source was towed behind a second ship while the borehole receiver stayed at a fixed depth. The investigation of these data focuses on possible seismic anisotropy and converted shear waves. In this study, we present initial observations from a walkaway VSP experiment at Site 994.

Study area and data acquisition geometry
Three seismic profiles were shot over Site 994 (**Fig. 1**) with a 2*105 in^3 GI® airgun that was towed behind the *R/V Cape Hatteras.* Three-component geophones were clamped in the

borehole at 480 m and 650 m beneath the seafloor (mbsf). The water depth was 2800 m. The signals were recorded on the drillship, the *D/V JOIDES Resolution.* A half-spread shooting profile extending 7 km SW of the drill site was acquired at the shallower receiver position (D01), a full-spread profile of 14 km with the receiver at the deeper position (D02). After drilling was completed, we deployed a 4-component ocean bottom seismometer (OBS, with 3 geophones and 1 hydrophone) at the seafloor at Site 994. For further data analysis, this OBS can be regarded as an additional VSP receiver station at 0 m beneath the seafloor. The corresponding shooting profile was 13 km long in each direction. Single channel seismic data (SCS) were also acquired while shooting this line.

Fig. 2 presents the SCS data converted to depth using velocity functions from the zero-offset VSP studies. A bottom simulating reflector (BSR) marking the base of gas hydrate stability, which is very pronounced and continuous over the ridge crest, terminates or weakens considerably about 1 km northeast of the drill site. Strong reflections are observed slightly deeper at Site 994 and mark a zone of free gas, which is considerably thicker than previously thought (at least 250 m [7]). The presence of free gas is clearly documented by low P-wave velocities in the model derived from the zero-offset VSP at Site 994 (**Fig. 2**).

Compressional wave arrivals

As a first step to analyze the walkaway VSP data, we modeled traveltimes of the direct P-arrivals as a function of source-receiver (horizontal) offset using a V_p-model derived from the zero-offset VSPs. Computed traveltimes match actually observed arrival times well at zero-offset (**Fig. 3**). However, at larger offsets, the predicted arrivals are considerably later than the traveltime picks in the data. This indicates that rays, which arrive at non-normal incidence, travel faster than predicted by the velocity function used for our modeling.

We can fit the data fairly well by laterally increasing V_p by 10% in the sediment column (keeping V_p in the water column constant) in both directions within 800 m from the drill site. A lateral increase of V_p in both directions, however, would be hard to explain geologically and contradicts the zero-offset V_p-profile at Site 995, about 2.7 km northeast of Site 994[7]. We therefore interpret this effect as an indication for transverse V_p-anisotropy; i.e., velocities of a horizontally traveling wave are higher than that of a wave traveling at normal incidence. Anisotropy has been commonly found in marine sediments[8]. The depth of anisotropic layers and the degree of anisotropy is the focus of on-going data analyses at Site 995, where profiles were acquired at eight receiver locations. Results from these studies are essential for distinguishing lateral P-wave velocity variations from anisotropy.

Shear wave arrival

One of the main aspects of acquiring wide-angle profiles with a 3-component receiver at the seafloor or in a borehole is the possibility of recording S-waves converted from P-waves. We investigated the horizontal components of VSP and OBS data for possible S-arrivals, which are expected to be considerably slower than P-wave arrivals. Fig. 4 shows the horizontal components of VSP receiver station D02 and of OBS O3. Several slow arrivals can be clearly identified in both the VSP data and the OBS. Unfortunately, the data from the other VSP stations do not display these arrivals because of a higher noise level caused by bad weather.

Our first concern was to test, whether any kind of tube waves could cause the arrivals in the VSP data. We could not perform a polarization analysis because the second horizontal component had malfunctioned at this receiver station. Therefore, we investigated traveltimes as a function of offset: Assuming that the latest arrival of a hypothetical tube wave would have been generated at the seafloor, we computed the moveout expected for a receiver at the seafloor (which is the moveout of the P-wave arrival in the OBS). We then shifted this function by a constant value until it matched the observed P-wave arrivals at near-offsets. Assuming that each ray of a tube wave has to travel the same distance through the borehole, the moveouts should match, as illustrated in fig. 5. They clearly do not match. The most reasonable explanation for the observed arrivals, which are slower than the direct P-wave, is that they are shear waves converted from P-waves at different depths.

Analysis of the traveltimes of these arrivals is not yet completed. Both the depth of conversion and V_s are unknown. We attempt to constrain both values by matching the traveltimes at near-offset and the moveout at further offsets. This concept is similar to a velocity analysis of common midpoint gathers in conventional multichannel seismic data. However, we must use relatively time-consuming raytrace forward modeling to develop the velocity model instead of semblance analyses.

We also tested, whether the slow arrivals on the OBS may be shear waves. In this case downgoing P-waves are converted to shear waves during reflection. A relatively strong arrival occurs at about 4 s (near-offset) in the northeastern section of the profile (**Fig. 4**). Because this reflection cannot be seen in the hydrophone data and is only very weak in the vertical component of the OBS, we interpret it as a shear wave. We speculate that this arrival may have been generated at the BSR, which is prominent on the northeastern side of the drill site and terminates to the southwest. The relation of V_s as a function of V_p determined empirically by Castagna et al. (1985)[9] in siliceous sediments is widely used to estimate V_s in shallow marine sediments, e.g. for many of the waveform analyses of BSRs (e.g. ref. 10). We therefore used this relation to obtain a first V_s-function of the subbottom from the P-wave velocity structure. The computed traveltimes of a downgoing P-wave, which is converted at the BSR during reflection into an upgoing S-wave, are shown in fig. 6. Traveltimes match surprisingly well, considering that we did not adjust the model at all. Hence, we suggest that this arrival is an upgoing shear wave generated at the BSR from a downgoing P-wave. Several other slow arrivals, which do not appear in the hydrophone or vertical component data, are also interpreted as S-waves. Constraining the depths of the conversion points is not straightforward and will require a similar analysis as proposed for the VSP arrivals.

Physics of a compressional to shear wave conversion point

Shear wave arrivals recorded both at the seafloor and at the deeper VSP station suggest, that at least some of the conversion points are located in the zone of low normal-incidence P-wave reflectivity (SCS data, e.g. fig. 2). This finding is intuitively not easy to understand. Therefore, the physical property changes required to generate P- to S-conversion in a zone of low P-wave reflectivity were investigated. We modeled the amplitude of S-waves generated from P-wave reflections using the Zoeppritz equations (1919)[11] and computed synthetic seismograms using the reflectivity method of Kennett and Kerry (1979)[12]. We kept density (ρ) constant, because changes in ρ would lead to P-wave reflections at normal incidence. Seismic quality factors Q, describing attenuation, for the reflectivity modeling were set to typical values for marine sediments (for P-waves, Q_p=200, for S-waves, Q_s=50, e.g. ref. 13). In our simple models the seafloor was at 2800 m; depth of P- to S-conversion was set to 200 mbsf and the VSP receiver was at 400 mbsf.

In our first model, we assumed V_s to be of 300 m/s in the layer above the conversion point, 400 m/s in the layer beneath it. V_P in the upper layer was set to 1600 m/s. These are realistic velocity values. Assuming a constant density, the shear modulus μ is the only parameter which controls changes in V_s, whereas V_p is determined by both μ and the compressional modulus K (ref. appendix for equations). We now assumed, that only μ would change at the conversion depth. We computed μ for both layers from V_s and ρ. K in the upper layer was calculated from μ, V_p, and ρ. Finally, we computed V_p in the lower layer assuming a constant K. Resulting valued of V_p demonstrate, that in the soft sediments at the Blake Ridge, V_p depends mainly on K and even a large change in μ would not result in a significant change of V_p. (**Fig. 7**). Our modeling results show, that it is physically possible that a good P- to S-conversion point does not appear as a strong reflection in normal-incidence data. We also tested a second model, in which we changed V_p drastically and left V_s constant.. In this case, no P- to S-conversion would be expected. Hence if assuming a constant density, changes in V_s and consequently μ clearly control P- to S-conversion.

This does not necessarily apply to the free gas zone, since strong density variations may also cause P- to S- conversions. Free gas is not expected to cause a considerable change in V_s based both on theoretical studies and on laboratory measurements[14].

Are variable-offset VSPs suitable for in-situ gas hydrate quantification?

It is too early to discuss the causes for P- to S-conversion at the BSR. BSRs often mark the base of gas hydrate zones. Assuming, that the conditions for P- to S-conversion are matched at BSRs in other regions, our findings suggest that 3-component VSPs are a good technique to obtain the S-wave velocity structure in hydrate-bearing sediments. Above the BSR, i.e., in the gas hydrate zone, S-wave data might be recorded by generating P-waves at a constant offset, large enough to ensure P- to S-conversion at the BSR. Closely spaced receiver stations in the borehole with the S-wave "source" being the BSR will allow a determination of V_S from traveltimes of first arrivals similar to a zero-offset P-wave VSP. Some slight geometrical corrections still need to be applied to account for the offset. Together with a zero-offset VSP and density data, results from such an experiment would give the whole set of seismic parameters which are necessary to describe an isotropic medium: ρ, V_p, V_s, Q_p, and Q_s. Q_p was determined on Blake Ridge VSPs[15], Q_s might be assessed in the same manner as Q_p.

Towing the source and acquiring variable-offset data gives additional information on anisotropy. Hence, apart from shear wave anisotropy, a walkaway VSP experiment above BSRs may provide all seismic parameters of an anisotropic medium. The question of how these properties relate to hydrate content in the sediments, however, remains unresolved. Extensive laboratory studies will probably be the best way to approach this question.

Conclusions

First results from a walkaway VSP on the Blake Ridge, combined with an OBS, suggest the following: 1. P-wave anisotropy is occurring in the sediments and has to be taken into account when investigating lateral V_p-variations from wide-angle data. 2. Several conversion points from P-waves to downgoing S-waves exist above the VSP receiver station at 650 mbsf. 3. The BSR is a good source of converted upgoing S-waves from downgoing P-waves. 4. P- to S-conversion in the zone of low P-wave reflectivity is linked to changes in μ and consequently V_s, rather than V_p. Therefore, V_s must change considerably within the hydrated sediment column.

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Appendix - Computation of changes in V_p from changes in μ

We computed V_p from the change in μ which corresponds to a given change in V_s: In the layer above the conversion point, we set velocities and density to typical values in these types of sediments (ref. text). K and μ can be computed from (e.g., ref. 16):

$$V_p = \sqrt{(K + \tfrac{4}{3}\mu) / \rho} \qquad \text{(A-1)}$$

and

$$V_s = \sqrt{\mu / \rho} \qquad \text{(A-2)}$$

We then assumed a V_s increase at the conversion point, determined μ for the lower layer from (A-2) and computed the corresponding change of V_p from (A-1) assuming constant K and ρ.

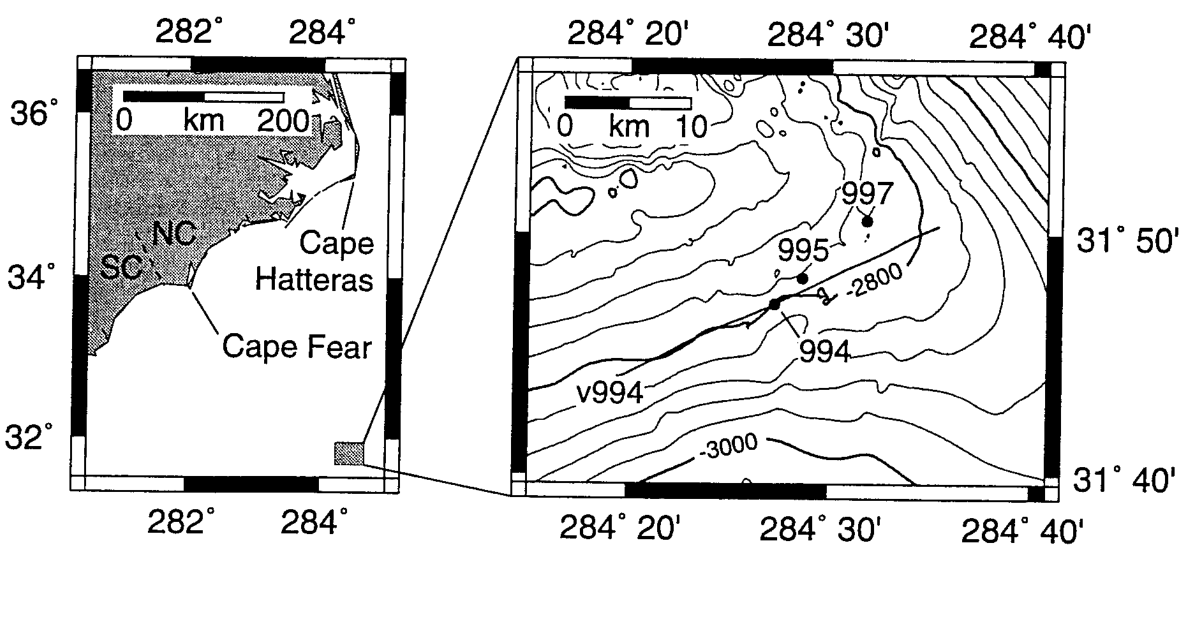

Fig. 1 - Map of the study area and location of seismic line v994 together with ODP drill sites. NC: North Carolina, SC: South Carolina.

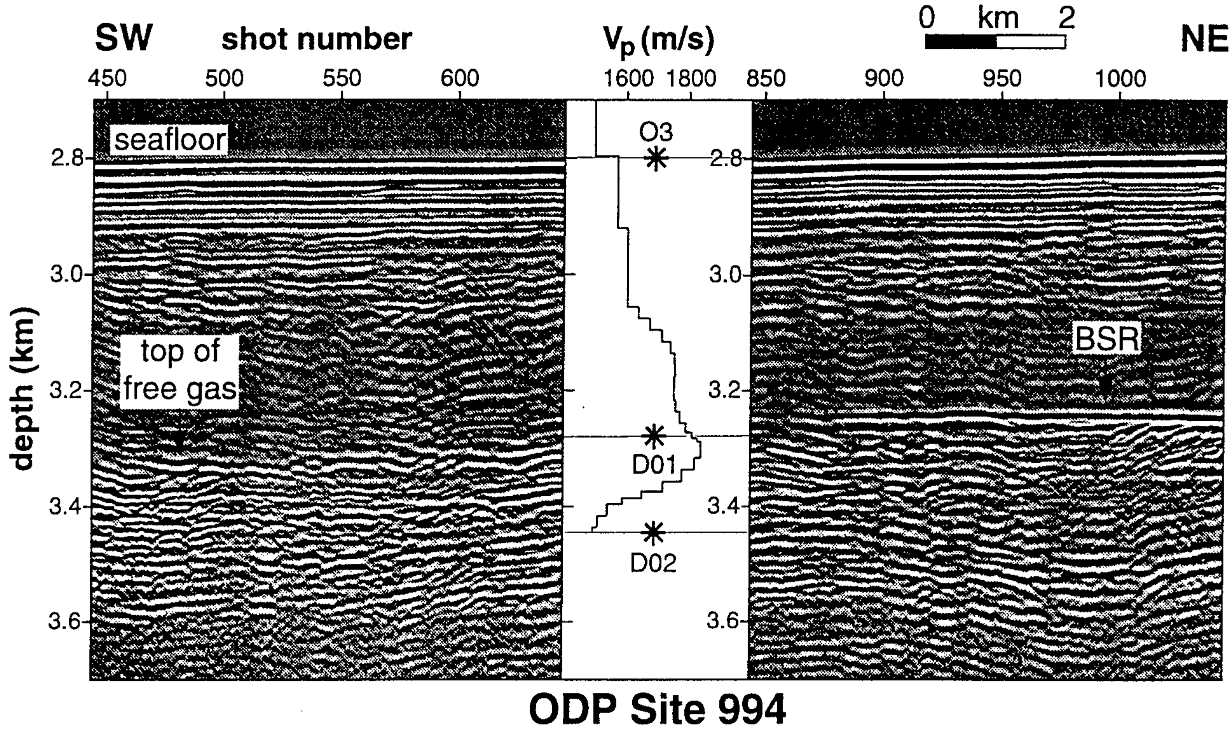

Fig. 2 - Section of the SCS profile acquired along with the VSP/OBS experiment. The inset shows the P-wave velocity profile determined from zero-offset VSPs[7] together with the depths of the two receiver stations for the walkaway VSP (D01 and D02) and the OBS (O3).

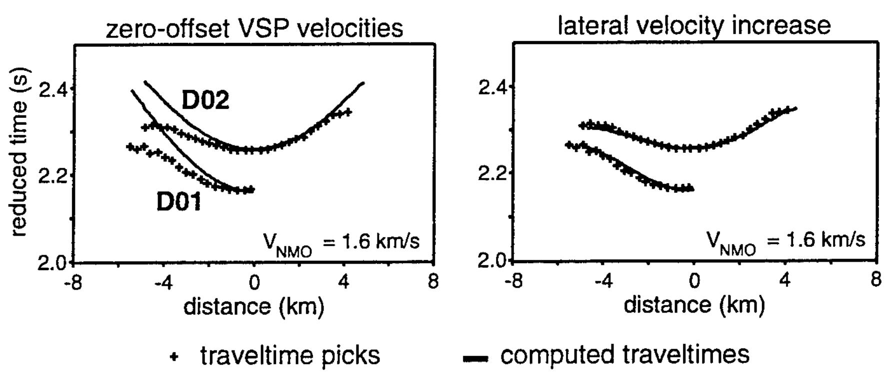

Fig. 3 - Comparison of observed traveltimes with computed traveltimes using the velocity function from fig. 2 (left). The data are plotted with a normal moveout correction (NMO). Introducing an artificial lateral velocity increase of 10% within 800 m from the borehole in the sediment column improves the fit significantly (right). This is interpreted as indication for anisotropy in the sediment column.

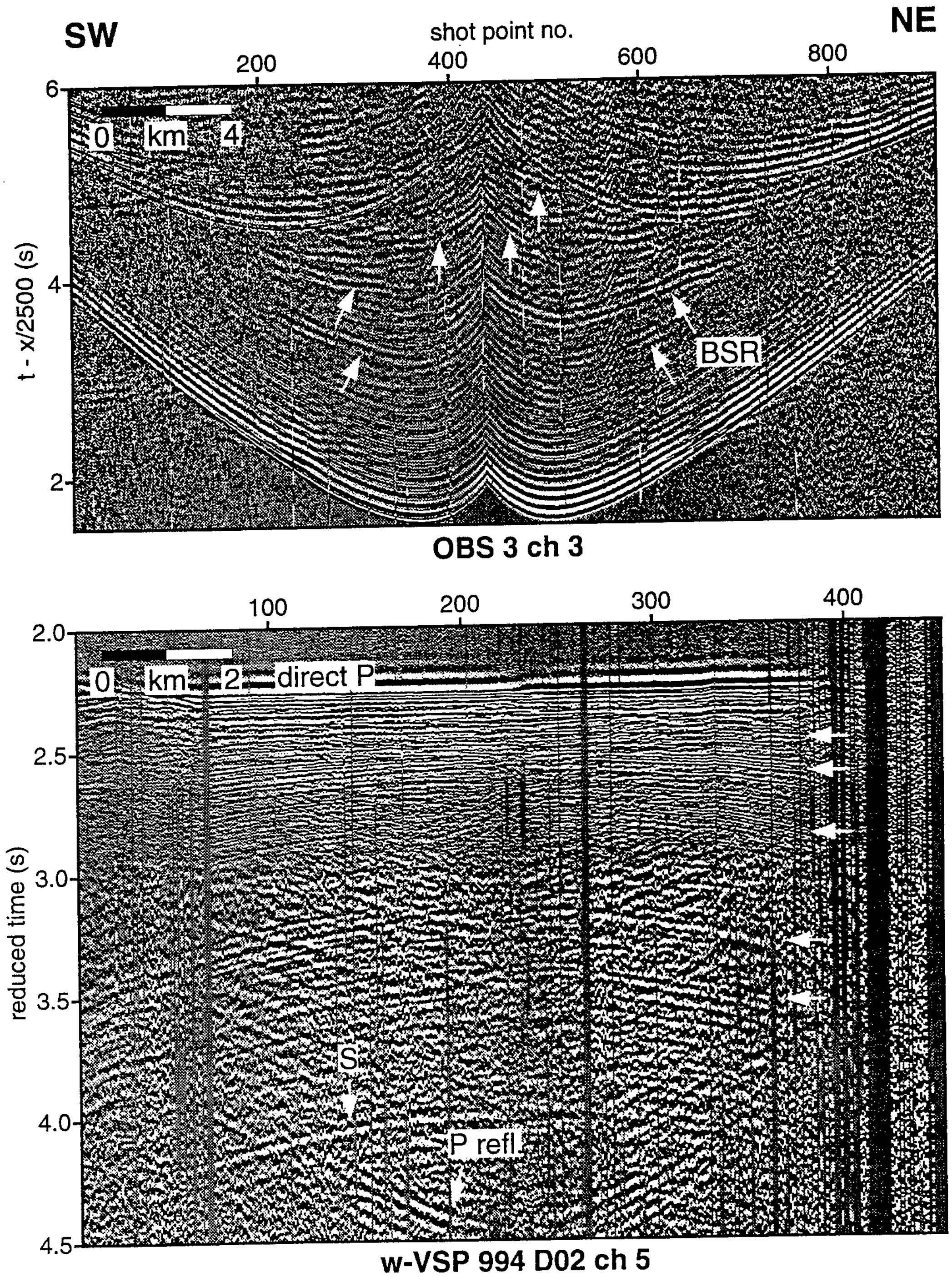

Fig. 4 - Horizontal components of OBS (top) and receiver D02 (bottom). The OBS data are plotted with a reduction velocity of 2.5 km/s. The data were frequency filtered. Arrows indicate slow arrivals which are interpreted as shear waves. The arrival labeled "BSR" is referred to in fig. 6. The VSP data are shifted such, that the direct P-wave arrival is horizontal. Downward bending arrivals are slower than the direct P-wave and interpreted as S-waves. Data were frequency filtered and deconvolved. The change in frequency content between 2.8 and 3.0 is caused by time-varying filter and deconvolution operators. "P refl." denotes a P-wave reflection, arrows mark S-waves, "S" labels the arrival shown in fig. 5.

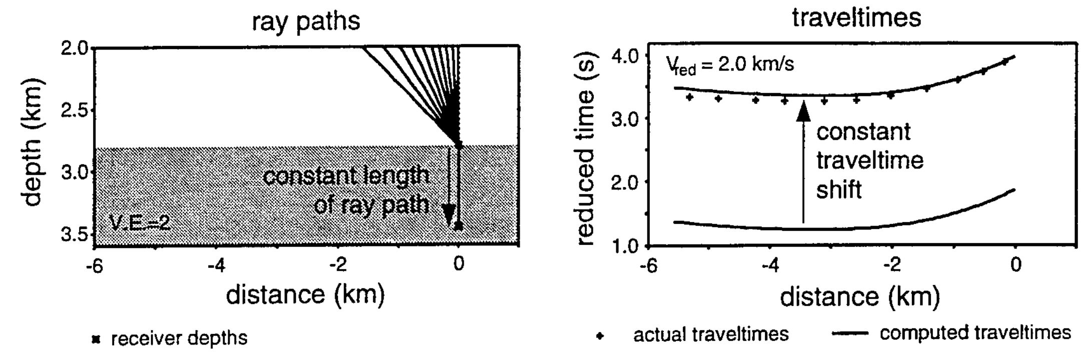

Fig. 5 - Computation of the moveout of any tube wave generated at the seafloor (solid line). Because of the vertical travel path along the borehole, traveltimes must be the same as for a receiver at the seafloor shifted by a constant value. The difference in moveout at 5 km offset is almost 0.2 s.

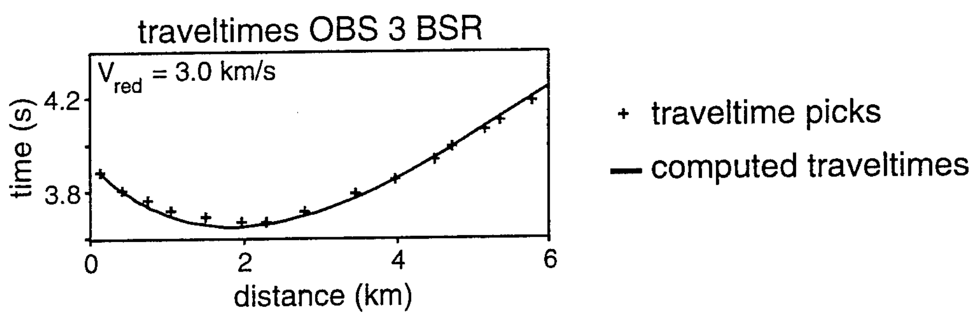

Fig. 6 - Comparison of traveltime picks from reflector "BSR" in fig. 4 and theoretical traveltimes assuming this arrival is a S-wave generated at the BSR northeast of the drill site. Castagna et al.'s (1985)[8] relation was used to estimate V_s from V_p.

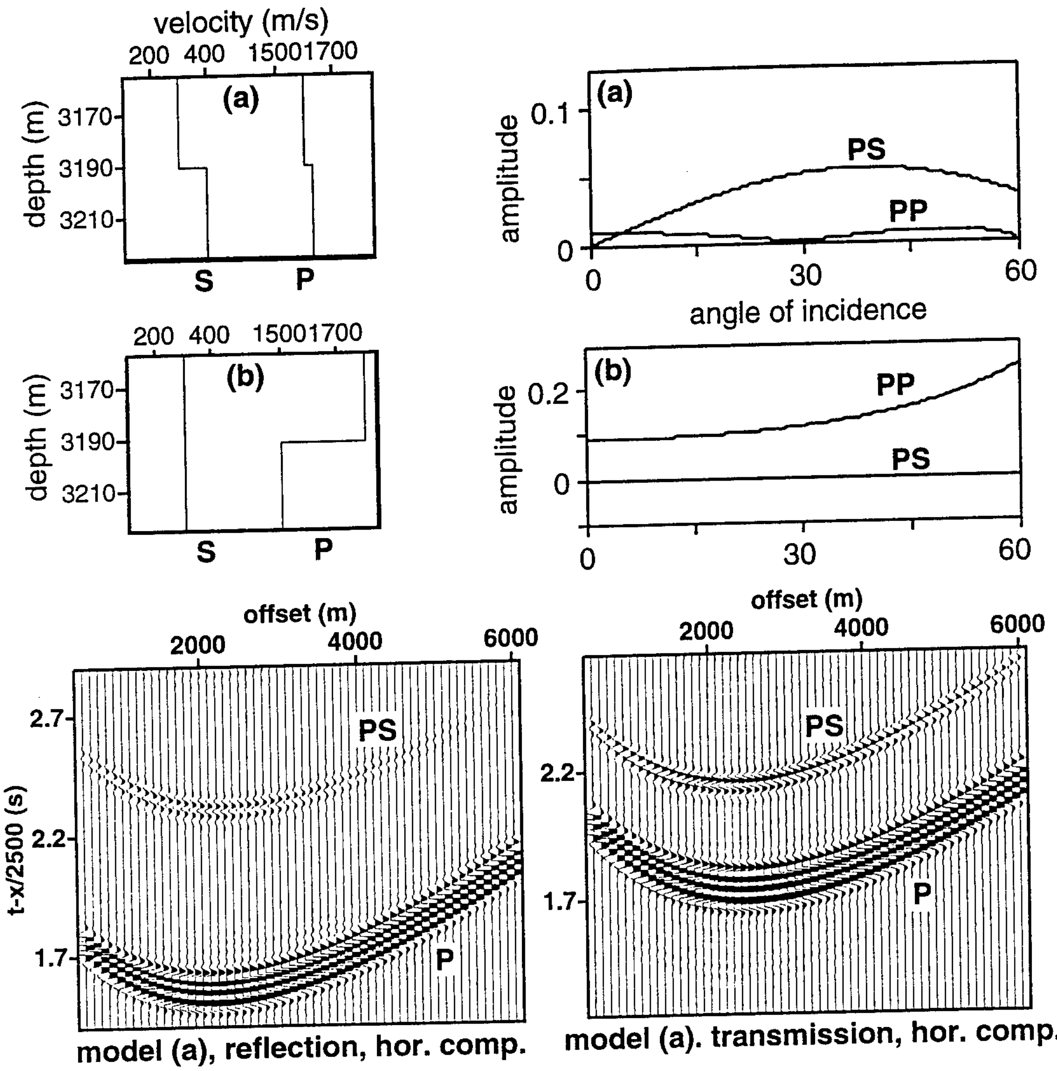

Fig. 7 - Modeling of P- to S-conversion. Top left: velocity models. The P-wave velocity in (a) was computed assuming a constant bulk modulus (refer text). Top right: absolute amplitude of reflections for both models, "P" denotes the direct P-wave arrival, "PP" P- to P-reflection, "PS" P- to S- conversion. Bottom: Synthetic seismograms for upgoing shear waves (left) and downgoing S-waves (right) for velocity model (a). Scaling of the traces is such that 0.1 times the amplitude of the incoming P-wave corresponds to 1 wiggle excursion. Refer to text for further details. A change in shear modulus corresponding to a shear wave velocity increase from 300 to 400 m/s is sufficient to create significant converted shear waves without considerable P-wave reflections (a), whereas a mere change in P-wave velocity does not generate converted S-waves (b).